EARTHQUAKE-RESISTANT STRUCTURES

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During 1926, observatories, throughout the world, recorded thirty-two thousand earthquakes, nearly a hundred of which were destructive to lives and property. DeBallore, the French authority on frequency and geographical distribution of earthquakes, catalogued a hundred and seventy thousand before 1904, and to date over a half million have been listed. Thus, it would appear that earthquakes are not the infrequent visitations many suppose. When the statement is added that fourteen million people have perished in known convulsions the importance of the subject assumes its proper role.

Seismologists say that earthquakes originate at depths of a few miles, from one of two causes—the breaking of the strata from accumulated pressure or from volcanic explosions. In this paper we are not concerned with frequency, geographical distribution or causes, but will deal with the phenomenon itself and steps to minimize its destructivity.

After a scholarly study of the earthquake disaster at Naples in 1857 and investigation of the production and propagation of waves, Mallet defined an earthquake as "the transit of waves of elastic compression through the crust of the earth."

From the origin, the vibrations are transmitted in all directions, and during their passage through a diversity of materials, through bodies of water, marshes, mountains and valleys, they are somewhat distorted, but seismograph records prove that these waves are many miles in length and the distortions are, therefore, not appreciable on a building site.

Earthquake waves are generally classified into three primary oscillations, caused directly by the impulse, and one secondary undulation, the result of the primary vibrations. Of the primary types, we have those which cause an up-and-down motion or vertical waves; the direct horizontal which tend to overturn on a horizontal axis to and from the origin, and the transverse vibrations which oscillate at right angles to the direct horizontal movements. (Sometimes the second and third types are turned ninety degrees due to the nature of the impulse at the origin of the earthquake. As buildings are designed for attack at any angle, this does not affect our investigation.) The following sketches and explanation will make the nature of the vibrations clear:

From the origin, down in the earth, waves move directly to the surface, striking buildings from beneath, a considerable blow. Because persons seem to be most sensitive to vertical shock, the strength of these forces has been exaggerated and to them have been attributed damage which they do not cause. These vibrations are the first to reach the outer crust, and because they bear a rough relationship to the strength of the more destructive movements to follow, one inured to seismic disturbances can tell the intensity of the dangerous part of the earthquake, immediately upon the arrival of the vertical shocks.

Next of record are the direct horizontal movements, those which tend to overturn to and from the origin. These are the ones which wreck improperly designed buildings with their great intensity and the fact that they strike in a direction not considered in ordinary gravity design, which provides for vertical loads only.

**A paper read before the Los Angeles Section of the American Society of Civil Engineers, January 12, 1927, and in substance before the State Convention of the American Water Works Association in San Diego, December 12, 1926.*

The transverse tremors are felt last. They are due to the passage of the impulses through solids. In a few earthquakes twin origins, detonating one after the other, as sometimes happens in the Tokyo-Yokohama district, have caused a whirling motion, but this is so unusual as to be negligible.

good safeguard. The crushed sidewalks and raised ground around large buildings in Tokyo and Yokohama testified to the surface disturbance in the 1923 disaster. However, surface waves are possible only on soft ground and are considered "special cases" owing to particular sites.

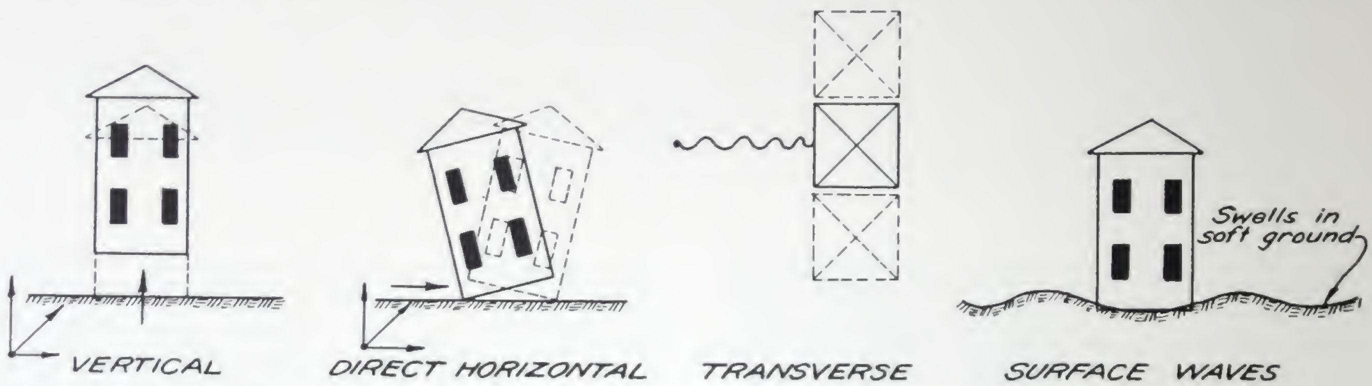


Fig. 1

The primary vibrations set up disturbances in bodies of water, and soft and especially wet ground, which are caused to heave and roll like ocean swells, sometimes with very destructive effects, striking structures as breakers do a coast. These may be several feet high and but a hundred feet in length. Because the vertical and the transverse vibrations are relatively feeble, only the effects of the direct horizontal movements are observed in these secondary waves.

Due to their invention of the recording seismograph, Doctors Milne and West at the University of Tokyo in 1883, learned much of the true nature of earthquake vibrations. The classifications of the waves and their relative speeds were confirmed by super-imposing records from seismographs registering in three planes. Further, and most important of all, the surprising regularity of seismograms, from points a short distance from the scene of the

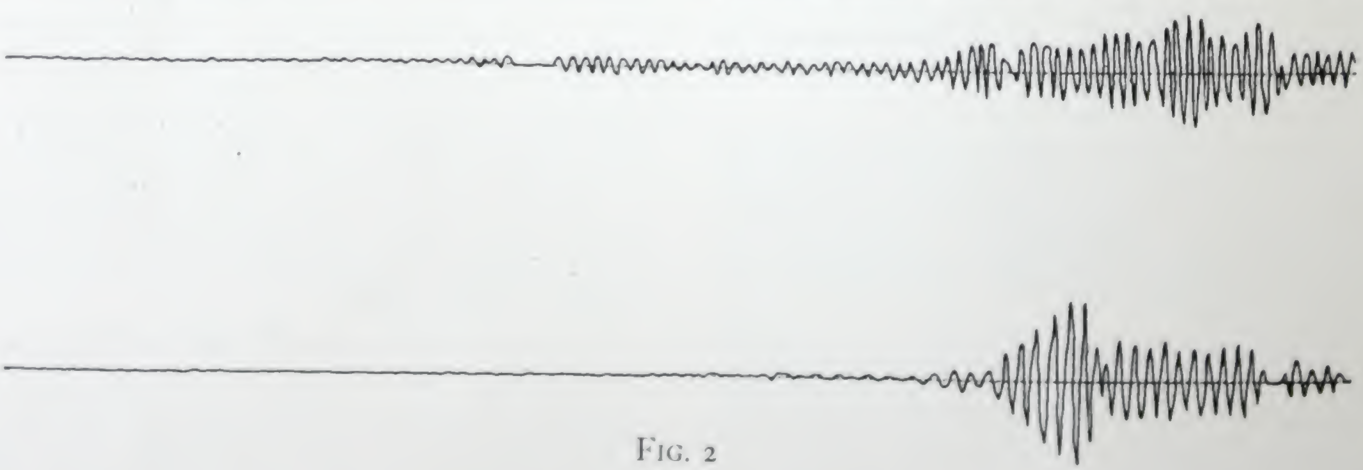


Fig. 2

The Romans founded their structures well below the soft upper soil and dug pits outside their important buildings. The wise builder sinks his structure below the shifting surface and an areaway at the side of a building is a

disturbance, showed the vibrations to be simple harmonic motions, like the swinging of a pendulum and, as such, the forces of an earthquake are expressed by Newton's Second Law of Gravitation:

Force=Mass x Acceleration

As "mass" is the property of the object acted upon, "acceleration" must be the measure of the earthquake. This explains why some disturbances of considerable movement have been less destructive than others of less amplitude but of greater "swiftness."

Returning to the primary waves, there are three still under consideration. For the vertical vibrations we find that the maximum value, from authentic data, is an acceleration of five feet per second per second. Inserting this in the formula:

$$F = M \times Acc. = \frac{\text{Weight}}{\text{Acc. of gravity}} \times \text{Acc. of Quake}$$

$$= \frac{W}{g} \times a = \frac{W}{32} \times 5 = .155W$$

we find that the maximum increase or decrease in the weight carried by the vertical members of a structure might be 15½%. As columns are designed with a factor of safety of four or five, bearing walls are supposed to have at least this margin and foundations are intended to carry but a small proportion of their safe load, it can be plainly seen that the vertical waves have no effect on buildings and may be neglected. (This must not be confused with the direct load on the columns induced by the horizontal waves which on exterior and especially on corner columns may be considerable.)

As buildings are designed to resist overturning or vibrations against any face, one possibility of damage from the horizontal waves would be of both acting at the same time and causing torsion. Seismograms indicate that both do not reach their maxima at the same instant, but if they did, the maximum ratio of the transverse to the direct horizontal vibrations would cause a deflection of the larger force from its line of action of less than ten degrees. No damage from torsion has been observed by investigators to my knowledge. It is only considered when the center of gravity of the plan of a structure is some distance from the geometrical center. This disposes of the transverse tremors.

But before we give the direct horizontal waves further study, let us note some of the phenomena which sometimes accompany seismic disturbances, tidal waves, landslides, and sudden depressions or elevations, sometimes of considerable magnitude. In 1923, according to the reports of the Japanese Navy, 1300 square miles of Sagami Bay sank over a thousand feet and thousands of acres of hydraulically filled land around Tokyo Bay settled from two to over three feet. Slides have caused great losses of life and property in Japan, China, Switzerland and Italy. Fissures have opened and on a few occasions swallowed towns of several thousand persons and tidal waves have swept hundreds of villages and scores of thousands to destruction in a single catastrophe. But all of these are induced by peculiar characteristics of limited areas, whereas our discussion is of "standard seismic conditions" which prevail over the larger disturbed territory which, on occasions, has exceeded two million square miles, two-thirds the area of the United States.

Our consideration is now reduced to the direct horizontal oscillations and to discover their effects on a complicated structure, let us first examine their action upon a regular prism.

We know that the weight of a body acts vertically through its center of gravity to maintain the body erect and if the prism is subjected to a horizontal force at the base there is set up a moment of resistance around the edge of the foundation in the opposite direction. The weight is considered concentrated at the center of gravity and, in this case, half the base is the lever arm. Because the moment of resistance is exactly equal, although in a counter direction, and the body is oscillating, which makes the direction unimportant, it is permissible to consider the inertia and the earthquake force as two forces acting through the center of gravity of a structure whenever it is subjected to an earthquake. The force necessary to overturn is computed in figure 3.

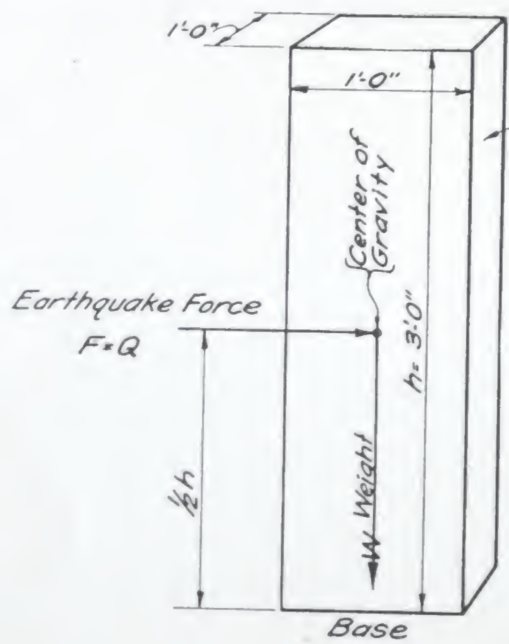
Considering the building, shown in figure 4, we have the two forces acting "W," the vertical or gravity weight, and "Q," the earthquake force, with the resultant "R," inclined from the vertical by the angle "X", whose tangent is Q/W. The structure will then be subjected to the stresses and will behave in quite the same manner as if inclined, alternately from one side to the other, the angles and the distances shown, even though buildings do not move more than a very few inches in an earthquake.

Date	Location	Acceleration Ft./Sec./Sec.	Authority	Angle "X"	Equivalent Hor. Displacement of top of 150′ Building.
1906	Marin Co., Calif.	6.6	Omori	12 deg.	31 feet
	San Francisco	3.5	"	6	16 "
1922	Tokyo, Japan	4.0	"	7	18 "
1923	Tokyo	9.0	"	16	41 "
	Yokohama	13.0	"	22	56 "
	Kamakura	16.0	"	26½	67 "
1924	Tokyo	6.6	Naito	12	31 "
1925	Santa Barbara	4 to 6	Butts	9	23 "

Now, it is evident that few structures can resist such deviations from the vertical, if no special precautions are taken, and this is all the more so when the movement is oscillatory, being repeated many times, the forces searching out, as it were, the weaker places, causing cracks, and if continued for a sufficient length of time, or followed by other quakes, progressive failure. For this reason, buildings cracking in one disturbance are likely to fail in a subsequent tremor of much less violence, and repairs of earthquake damage should be executed with the greatest care.

Earthquake stresses are quite different from those induced by dead or live or even wind loads. Dead and live loads act vertically and ordinarily affect columns and other vertical supports in compression only. Wind loads act horizontally, are the product of the vertical surface and the wind pressure, do cause some horizontal bending and shear in the structure but to an insignificant amount compared with earthquake forces. Considering a ten-story 100′x 100′ concrete loft building weighing 25,000,000 pounds, the horizontal force induced by an earthquake of the intensity of the San Francisco disturbance on fairly good ground (acceleration 3.5 ft./sec./sec.) would be 2,750,000 pounds. A horizontal wind pressure of thirty pounds per square foot would produce a force of less than 400,000 pounds, or one-seventh of the force acting in an earthquake of moderate intensity. Also the seismic forces act through the centers of gravity of the structure while wind pressure is on the vertical surface. For these reasons designs cannot be provided to resist seismic forces by the simple expedient of allowing large factors of safety or heavier loadings on the usual basis of design. It can usually be shown that this practice actually increases the danger by adding weight indiscriminately with which the earthquake may wreck the structure.

It is assumed, for purposes of design, that the earthquake acts through several centers of gravity and in multiple-story structures these are assumed at the tops of the floors. Buildings are first designed for ordinary loads and then investigated for earthquake stresses. The dead and live loads reasonably assumed as



$$\text{Weight} = 150 \text{ lbs/cu. ft.} \times 3 \times 1 \times 1 = 450 \text{ lbs.}$$

$$\text{Force to overturn} > \text{Weight} \times \frac{\text{Base}}{2}$$

$$Q \times \tfrac{1}{2}h > 450 \times \tfrac{1}{2} = 225 \text{ ft. lbs.}$$

$$Q = Ma = \frac{W}{32}a = \frac{450}{32}a = 14.1a$$

$$14.1a \times \frac{h}{2} > 225$$

$$a > \frac{225 \times 2}{14.1 \times 3} = 10.7\text{′/sec/sec. to overturn}$$

Fig. 3

present at any one time, and the specified earthquake acceleration are the bases for determining the stresses. Investigations in New York City, a few years ago, showed that none of the office buildings were actually carrying more than ten pounds live load per square foot. Except for warehouses, at some time likely to be fully loaded, the use of similar proportions of the live loads usually required in building codes appears justified.

The floors should be as light as possible, consistent with the vertical loads they support and the rigidity which they must have. They constitute a large part of the weight which, when acted upon by the acceleration of the earthquake, stresses the columns, girders and walls. Of several loft buildings investigated the floors formed approximately 57% of the total weight above the foundations in reinforced concrete buildings and 67% of the weight in fireproofed steel framed structures. The story heights should be kept low to minimize the bending moments.

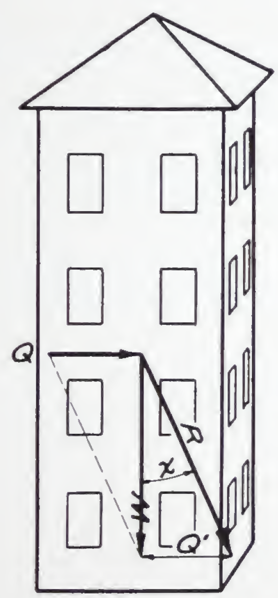


FIG. 4

In proportioning footings, the current practice of using a larger live load than ever exists tends to make the unit soil pressure higher in exterior foundations than under interior columns. This is injurious, from the standpoint of seismic design, as the disturbance tends still further to increase the soil pressure of outside footings and failures have sometimes resulted from this cause. For several reasons, principally because the inside foundations are likely to be drier and better protected from movements of the ground and from possible undermining, it seems reasonable that the interior footings should carry a heavier unit soil pressure and perhaps be designed for dead loads only, in office buildings, apartment houses, etc.

It is essential that there be no displacement of the footings and to this end they should be connected if the sub-foundation is not sufficiently hard to preclude movement. It is generally insisted that a single slab or a thoroughly inter-connected "floating" foundation is advisable; that short piles are better than long ones and that pile-followers should be sparingly used. The subject of foundations is a very important one but with the above high lights we must push on.

The calculation of seismic stresses in frames, such as office buildings, introduces the study of rigid frames and the relative rigidity of panels. For these investigations, the pioneers were extremely fortunate in possessing the services of recognized authorities on indeterminate structures, Doctors Abe and Naito. Through their efforts simplified methods for making these calculations were developed.

Another major problem is the period of vibration of the structure and that of the earthquake. In regard to this, let me quote from a paper by T. Okubo, Assistant Chief Engineer, Truscon Steel Company of Japan: "Assuming a perfectly rigid building set on a rigid crust, the movement of the structure will be the same as the crust itself. Under these conditions, the effect of the earthquake can be calculated with accuracy by the simple method of multiplying the mass of the building by the acceleration of the earthquake and designing the members accordingly. But actually both the crust and the building are elastic bodies and the whole is complicated by the period of vibration of the structure. . . .

"In case the period of the building is close to that of the disturbance, the two may synchronize and the additive effect make the motion of the building larger and larger until collapse must result if the vibrations continue."

Both of these theorems are understood, if one will stop to think that the motions of a block on a shaking table can only be those of the table itself and under the second theorem that the additive effect of a slight impulse on the motion of a pendulum, if of the same period as the swinging weight, is very great.

It has been found that buildings can be constructed to resist any movements imposed by the earthquake itself and under the above postulates it is desirable that buildings be constructed as nearly rigid as is economical, or at least that their periods be as far as possible from those of the earthquake. It is possible to calculate the period of vibration of a proposed structure from plans and specifications as accurately as it can be measured on the completed building and data on thousands of destructive disturbances indicate that their periods lie within narrow limits. It is thus possible to avoid resonance with its evil effects.

Frequently during a discussion of seismic design, I am asked what intensity we should assume as a basis for computing earthquake forces and investigation leads me to believe that the following are pertinent considerations in arriving at a proper acceleration:

Everywhere structures should be built with a view to minimizing earthquake damage for *there are no areas which are free from this menace.*

The degree to which buildings should be made earthquake resistant, depends on four factors:

First, the particular site and the character of the sub-foundation. It has been definitely demonstrated that the intensity and destructivity of an earthquake is dependent on the sub-foundations, almost entirely, i.e., that the impulses at the origin of destructive quakes have not been so varying in intensity but the sub-foundations through which they have acted made their differences in destructivity.

Second, the character of the structure, its use, and the consequences of collapse. On this basis, it seems reasonable that a school, a theatre, or other place of assembly where large numbers of people might be trapped, should be better protected than a warehouse or a garage.

Third, the seismic record of the territory should be investigated, although this is not to be taken too seriously. Kamakura, the home of the famous bronze Buddha, some twenty miles from Yokohama, had apparently a firm foundation for its reputed immunity, after freedom from seismic disturbance of over six hundred years, since May 20, 1293. The most violent vibrations of the terrible disaster of the 1st of September, 1923, were felt here and at the nearby naval base, demolishing nearly every structure in the area, wooden buildings faring no better than those of heavier materials with less elastic strength.

San Francisco has suffered more earthquakes than any large city in the United States but the lower Mississippi and the St. Lawrence River Valleys have been the scenes of much heavier shocks and more displacement of the terrain than has been known to occur elsewhere on this continent.

Fourth, the cost of making provision for earthquake stresses should be studied. It can be shown that an adequate allowance for office buildings, even with poor sub-foundations, is four or five per cent, slightly more for buildings of long span and great story heights. When the low cost of protection is known it will not be a stumbling block.

Types of Buildings

Studies of all modern earthquakes and personal observation in Japan in 1923 and 1924, Santa Barbara in 1925 and Calexico in 1927, lead to the following conclusions, held generally by engineers in Japan:

Wood-frame structures for ordinary residential, commercial, and industrial purposes, as usually designed and ordinarily well executed, without any special attention to earthquakes, if in good condition, possess sufficient strength to withstand anything but such a terrific disaster as completely wrecked the wooden hotel in Kamakura in 1923. Wooden structures add considerably to the fire hazard and where they are constructed, a special attempt should be made to provide an efficient fire-fighting system, which will itself be intact after a severe disturbance. In many earthquakes fire has destroyed more lives and property than the convulsions of the quake. Fully half of the quarter million casualties and over seventy-five per cent of the five-billion-dollar property damage in the Tokyo-Yokohama tragedy were due to the conflagration.

The usual bearing-wall construction of adobe, brick or stone is dangerous as is all block construction not thoroughly tied together with a frame. Since the many sad experiences in San Francisco and Santa Barbara, and the destruction of all brick bearing-wall structures in Yokohama, the advocates of this type of construction have suggested certain changes.

We are advised to tie the structures together at the floor levels with reinforced concrete belt courses and to use more and better anchors to floor joists, rafters and veneer. These are wise measures but the structures produced are still rule-of-thumb designs which have not been, and sometimes cannot be, analyzed. Their resistance to seismic disturbances is therefore largely guesswork. It must also be pointed out that the stresses are largely in the vertical not the horizontal members.

It can be shown that bearing-wall construction, is surpassed by *skeleton structural steel or reinforced concrete structures* in three particulars, positive determination of seismic and all other stresses; general resistance to shocks, even when not designed for earthquakes, and lower cost.

Bearing-wall structures are indeterminate mathematical problems while frames can be analyzed satisfactorily. After the forces have been determined it is necessary to distribute provision for them between the frame and the walls. This is done on the basis of the relative stiffness of bents and wall panels. There are two types of walls, stiffener walls which should be strong enough to resist the tendency to distort, and division walls which should be capable of some distortion without damage.

Light brick and hollow terra-cotta filler walls in structural steel or reinforced concrete frame buildings, maximum height one hundred feet, did not show a good record in Japan. Where well laid brick walls, minimum thickness thirteen inches, or reinforced concrete walls were used the damage was slight, unless the walls enclosed very large areas or were pierced by many poorly framed openings. The required dimensions of stiffener walls can be definitely determined and the stress induced by an earthquake of a given intensity in a wall, column or girder can be satisfactorily calculated.

The use of vertical diagonal bracing to strengthen the frame has been extensively advocated and, if it can be used without interfering with the layout of openings, is a definite and economical solution. Portal bracing in the form of knee and bottom braces is more common. The use of walls to give the required stiffness to a well connected frame has been found economical and to work well in practice.

If a building is to come off free of all damage it must have strong walls regardless of its frame. A good frame will certainly prevent collapse and the ideal building has light floors sufficiently rigid to compel the same deflection in all vertical bents, wall panels and columns and the girders, columns and walls designed and constructed of such materials as to insure ample strength to provide for that portion of the total horizontal forces which their rigidity demands.

The accompanying tabulation of the record of different types will emphasize the general resistance to earthquake shocks of skeleton framed buildings. It is especially to be noted that there have been no failures of structural steel frames although spectacular structures and those most likely to damage because of long spans, high story heights and slender proportions, have been of this construction. Those in the San Francisco disturbance were designed without much reference to earthquakes and the fact that they suffered very little damage is a tribute to their large reserve for such unexpected loads.

The question has frequently been asked what *type of building* is best for earthquake-resistant construction. Being intimately familiar with the design, erection and the cost of both reinforced concrete and fireproofed structural steel frame construction (I do not consider any other types over two or three stories in height suitable for resistance to earthquake and fire), I think it best to review the two types from various angles to make myself clear.

Height

There were no concrete buildings in Yokohama over four stories high and only one in Tokyo (which collapsed) over six stories. There were several towers in Yokohama and many buildings in Tokyo eight stories in height of structural steel frame construction, of which none failed although several were damaged. It might be incorrect to say that none of these were seriously damaged but it is a fact that none were razed during reconstruction. Many buildings of both types passed the earthquake test with no damage whatever. In San Francisco there was very little structural damage to skeleton steel frame buildings as high as eighteen stories. There were a number of failures of reinforced concrete structures in Santa Barbara, the highest, eight stories, being damaged rather severely. There were no strictly

steel frame structures in Santa Barbara nor any reinforced concrete buildings in San Francisco.

The records show that no concrete structures over seventy-five feet high have escaped severe damage or collapse in an earthquake while there are no failures chalked up against structural steel frame buildings 100 feet high in Japan or 300 feet in height in California. No lives have ever been lost in a steel frame building. Several hundred can be traced to the collapse of concrete structures. The record, even for the low concrete buildings which have been subjected to earthquakes, is not good. For buildings of over six stories it is very unfavorable.

Dependability

A reinforced concrete building is the product of rough field methods while structural steel frames, the vitals of a building, are shop and laboratory products with all the difference of scientific control in favor of structural steel.

Insurance

Without further investigation, except as to the fact that a structural steel frame is used, the insurance companies are willing to grant a lower rate on steel frame structures than on any other type of large building construction. Rates are in a state of flux but this discrimination will undoubtedly continue. When the difference in premiums on buildings and on contents is considered, steel frame structures with their slightly higher first cost are usually cheaper than those with reinforced concrete frames under almost all conditions.

COMPARATIVE RESISTANCE OF DIFFERENT TYPES OF STRUCTURES

EARTHQUAKE	TYPE			REMARKS
	Struct. Steel Frame	Reinf. Conc. Frame	Brick	
San Francisco, 1906. 3 to 6 ft. per sec. per sec.	Some damaged. No failures. 18 stories (200′) max. height.	*Only one badly damaged.	Generally wrecked.	No bldgs. designed for earthquakes.
Tokyo and Suburbs 1923. 8 to 10 ft. per sec. per sec.	†A number damaged but no failures. None razed for repairs.	17 collapsed, 29 badly damaged, 129 slightly damaged, 533 no damage.	Brick buildings if of first class quality generally stood. Walls were very thick and well layed.	
Yokohama 1923. 10 to 14 feet per sec. per sec.	†*No earthquake damage.	4 collapsed, 5 badly damaged, 8 slightly damaged, 16 no damage by quake.	All destroyed regardless of quality. Max. height four stories.	Some bldgs. designed for quakes.
Kamakura 1923. 14 to 18 ft. per sec. per sec.	None.	A few, all wrecked.	All collapsed, including many wood frame buildings.	

*Not full frame structures. †Height limit, 8 stories (100′)
From this it would appear that Prof. Derleth's conclusions based on the San Francisco Earthquake of 1906 were correct:
"Class A (Structural steel frame) structures stand earthquakes admirably."
"Brick buildings are not capable of withstanding heavy earthquake vibrations."
"Frame buildings, well built, are adequate for earthquake countries."

Weight

Weight is a disadvantage in design to resist shocks. Pound for pound, a steel frame building is stronger than one of reinforced concrete and when it is added that a concrete building for the same purpose is much heavier, the advantage of the steel frame structure is apparent. Actual comparison of two designs for a store 100′x100′xten stories, showed the one of reinforced concrete sixteen hundred tons heavier than the fireproofed steel frame building.

Additions

From a seismic standpoint, it is essential that additional stories or annexes to a completed structure be thoroughly tied to the old building.

This cannot be done satisfactorily if the building is of reinforced concrete, but is easily accomplished if the frame is of structural steel.

Psychological Effect

For a long time after the Japanese disaster of 1923, none but engineers would consider the erection of heavy buildings of more than three or four stories, and practically all of the large buildings designed after that date were of structural steel despite the fact that steel structures in Japan are much more expensive than those of reinforced concrete. The Santa Barbara quake had the same effect on the popular demand. Of two structures of equal exterior damage, the public will use the one with a structural steel frame and avoid the reinforced concrete structure altogether. The steel frame structure has always had the greater confidence of the public for they can see what "makes it stand up." This is very important in a building to be used as a department store, a hotel, an office building or a theatre. Even as engineers, we have a feeling that a structural steel frame building is safe but we would like to have a look at the tests of the cement, the sand and the crushed rock, the amount of water used and the methods employed in placing the reinforcing steel and the concrete before we feel an equal assurance in the concrete structure, for we know better than anyone else that if any of these are faulty the strength of the structure is seriously impaired.

With this evidence, the answer must be: The structural steel frame building is the most satisfactory type of earthquake-resistant structure and when properly constructed according to sound design constitutes our best protection against earthquake damage.